Simulating potential growth and yield of oil palm (*Elaeis guineensis*) with PALMSIM: Model description, evaluation and application

M.P. Hoffmann, A. Castaneda Vera, M.T. van Wijk, K.E. Giller, T. Oberthür, C. Donough, A.M. Whitbread

A B S T R A C T

Reducing the gap between water-limited potential yield and actual yield in oil palm production systems through intensification is seen as an important option for sustainably increasing palm oil production. Simulation models can play an important role in quantifying water-limited potential yield, and therefore the scope for intensification, but no oil palm model exists that is both simple enough and at the same time incorporates sufficient plant physiological knowledge to be generally applicable across sites with different growing conditions. The objectives of this study therefore were to develop a model (PALMSIM) that simulates, on a monthly time step, the potential growth of oil palm as determined by solar radiation and to evaluate model performance against measured oil palm yields under optimal water and nutrient management for a range of sites across Indonesia and Malaysia. The maximum observed yield in the field matches the corresponding simulated yield for dry bunch weight with a RMSE of 1.7 Mg ha^{-1} year^{-1} against an observed yield of 18.8 Mg ha^{-1}. Sensitivity analysis showed that PALMSIM is robust: simulated changes in yield caused by modifying the parameters by 10% are comparable to other tree crop model evaluations. While we acknowledge that, depending on the soils and climatic environment, yields may be often water limited, we suggest a relatively simple physiological approach to simulate potential yield, which can be usefully applied to high rainfall environments and is considered as a first step in developing an oil palm model that also simulates water-limited potential yield. To illustrate the application possibilities of the model, PALMSIM was used to create a potential yield map for Indonesia and Malaysia by simulating the growth and yield at a resolution of 0.1°. This map of potential yield is considered as a first step towards a decision support tool that can identify potentially productive, but at the moment degraded sites in Indonesia and Malaysia.

1. Introduction

Oil palm is one of the most important oil crops in the world. Palm oil production is five times greater per unit land than other oil crops such as soybean or rapeseed, which together with the growing global demand for vegetable oil and biofuels drives its profitability (Sheil et al., 2009). Malaysia and Indonesia account for 81% of the total global production. In Indonesia six million ha are covered by oil palm with an annual production of 102 million Mg fresh fruit bunches (FFB). Malaysia produces 88 million Mg from four million ha. FFB yield in Indonesia averages 17 Mg ha^{-1}, and in Malaysia it averages 22 Mg ha^{-1} (FAO, 2013). The rapid expansion of oil palm cultivation is seen as a severe threat for the conservation of rain forest and swamp areas and their associated ecosystem services (Koh et al., 2011; Koh and Wilcove, 2007). For example, the area in Indonesia dedicated to oil palm production doubled from 2003 to 2011 (FAO, 2013).

Considering both the growing demand for palm oil and the environmental consequences of oil palm cultivation, two strategies have been proposed for more sustainable oil palm systems: (i) establishment of new oil palm plantations on degraded or pre-existing cropland sites only (ii) and the intensification of production in existing plantations to reduce the gap between actual and water-limited potential yield (Gingold et al., 2012; Sayer et al., 2012).

Within the context of the first strategy, Gingold et al. (2012) provide an assessment of extension and suitability of marginal areas for oil palm cultivation in Kalimantan (http://www.wri.org/project/potico). Based on social, economic, legal and environmental criteria marginal areas were classified qualitatively into groups with poor to good suitability for oil palm. Gingold et al. (2012) concluded that there is substantial scope for the expansion of plantations into marginal areas in agreement with Indonesia's national REDD+(Reducing Emissions from Deforestation and Degradation) scheme, but that the definition of 'degraded land' or 'marginal land' is still under debate. The exact extent of degraded land is unclear, therefore, estimates of yield that could be achieved in such sites are often lacking.

Within the context of the second strategy, comparisons of actual yields with records of the largest yields indicate the scope for yield intensification for existing plantations. In 2006, the IOI Group, one of the leading plantation groups in Malaysia, reported an average annual FFB yield of 38 Mg ha^{-1}, with an estimated oil yield over 8 Mg ha^{-1}, for their best performing estate. At company level (ca. 150,000 ha), average oil yields of 6 Mg ha^{-1} and FFB yields exceeding 27 Mg ha^{-1} have been reported. FFB yields higher than 40 Mg ha^{-1} have been recorded for single blocks in many estates in Indonesia and Malaysia (Donough et al., 2009).

As such data is site and year specific, and not available for sites without history of oil palm production, the use of simulation models offers a viable way to assess potential and attainable growth and yield (van Ittersum et al., 2013). The available models that simulate oil palm production are demanding in terms of the data needed for parameterization and running of the model (Combres et al., 2013; Dufrene et al., 1990; Henson, 2009; van Kraalingen et al., 1989). This makes them less useful for a scoping analysis of potential and attainable oil palm yield across a wide range of locations. The first mechanistic oil palm model, OPSIM, was developed by van Kraalingen (1985). It simulates potential growth and yield based on radiation and assumes no other production limitations. To run the model, measurements on vegetative development are necessary. OPSIM's demand for crop data is similar to that of another oil palm model, SIMPALM (Dufrene et al., 1990), which was parameterized for oil palm production in Africa. A recent oil palm growth model OPRODSIMv1 is able to simulate the growth of oil palm from the day of planting (Henson, 2009). This is a detailed daily time step model, which simulates growth based on solar radiation, and growth is limited by temperature stress, vapor pressure deficit and water availability. Essentially, OPRODSIMv1 is demanding in terms of daily weather input (solar radiation, net radiation, humidity or vapor pressure deficit, air temperature, actual to potential evapotranspiration ratio, rainfall and wind). Combres et al. (2013) developed a site-specific model to investigate flowering dynamics, intended to serve as a management decision tool. However, due to the need for high accuracy to assess flowering dynamics a large database is necessary to estimate cultivar and plantation characteristics (Combres et al., 2013).

A mechanistic oil palm growth model that is limited in its demands for input variables and physiological parameters, and, which therefore can be easily applied across a wide range of sites, is lacking. The objectives of this study therefore were to develop a model (PALMSIM) that simulates, on a monthly time step, the potential growth of oil palm as determined by solar radiation and to evaluate model performance against measured oil palm yields under optimal water and nutrient management for a range of sites across Indonesia and Malaysia.

While we acknowledge that, depending on the soils and climatic environment, yields may be often water limited, we suggest a relatively simple physiological approach to simulate potential yield, which can be usefully applied to high rainfall environments and is considered as a first step in developing an oil palm model that also simulates water-limited potential yield. We assessed the usefulness of the current version of the model as an exploratory tool for decision makers in the planning of land use for oil palm by creating a potential yield map for Malaysia and Indonesia.

2. Material and methods

2.1. General structure of PALMSIM

The simulation model PALMSIM consists of a plant growth module, which simulates the potential growth and yield of an individual oil palm stand on a per hectare basis, and a radiation module (Fig. 1). Potential production is defined in this case by radiation under otherwise optimal environmentally determined growing conditions: no growth limitation in terms of water or nutrient availability, and no incidence of pests or diseases (van Ittersum et al., 2013). The model also assumes uniform planting material and recommended canopy management in terms of pruning. Planting density is set to 143 palms ha^{-1} following standard practices in the oil palm industry (Corley and Tinker, 2003). However, planting density and also the pruning regime can be altered in the model.

The growth and the radiation modules are linked through a run module, which contains all the general settings of the model run. The oil palm growth module can also be used as a standalone tool for applications to individual sites when measured or estimated radiation values are available.

Using the combined plant growth and radiation modules the model can be run for any given site. PALMSIM simulates the growth and the yield of a palm stand using a monthly time step over a period of 30 years, which covers the maximum commercial life span of an oil palm plantation of 23–25 years. A detailed description of the model together with the mathematical equations is given in the Supplementary material; here we provide a general description of the model.

Incoming radiation is calculated based on latitude, slope, azimuth and monthly cloudiness index. PALMSIM is based on the assumption that under optimum conditions monthly growth of the plant is linearly related to the quantity of intercepted light (Monteith, 1977). Intercepted light is determined by the amount of incoming photosynthetic active radiation (PAR) and the capacity of the plant to intercept this light, using the leaf area index (LAI) and a light extinction factor (k) (i.e. Beer–Lambert law). LAI is calculated based on the specific leaf area (SLA) and the total biomass contained in fronds per hectare. Intercepted light is then converted into gross assimilates by applying a constant light use efficiency factor (LUE) (c.f. Combres et al., 2013). Frond biomass is produced by plant growth and removed by pruning.

Produced assimilates are first used to satisfy maintenance respiration (c.f. van Kraalingen et al., 1989). The remaining assimilates are allocated first to growth of the vegetative plant parts (roots, trunk, fronds). If minimal requirements for vegetative growth and growth respiration are satisfied, assimilates are used for generative biomass production (i.e. female and male flower production). The amount of assimilates used for male flowers are related to the vegetative standing biomass. Any remaining assimilates are used for female flower production. A growth respiration coefficient is applied for generative growth.

Bunch production is therefore considered to be source limited, except for young palms, where maximum bunch weight is dependent on the age of the palm stand. The model therefore predicts maximum total biomass production and yield, as well as the yield components and the weight of bunches produced at a certain moment in time.

2.2. Parameterization of PALMSIM

The input variables (Tables 1a, 1b and 1c) are based on values suggested in the literature or derived from the process-based models SIMPALM (Dufrene et al., 1990), OPSIM (van Kraalingen et al., 1989) and OPRODSIMv1 (Henson, 2009) (Tables 1a, 1b and 1c).

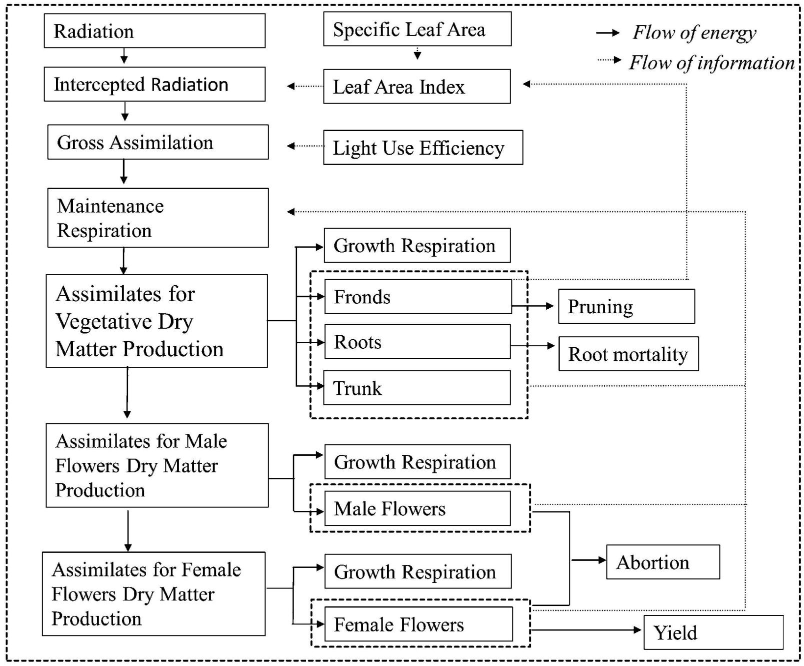

Fig. 1. Schematic overview of PALMSIM. Dashed boxes represent standing biomass.

2.2.1. Radiation, light interception and photosynthesis

Solar radiation is calculated from the cloudiness index, azimuth and slope following the method presented and tested in Augustine and Nnabuchi (2009) and Ruth and Chant (1976). Following Monteith (1972), PAR is assumed to be half of the total solar short-wave radiation. The standard value for specific leaf area in oil palm is 0.31 ha Mg^{-1} (Breure, 2003). Various values have been found for k in oil palm (Noor and Harun, 2004). The value of k is related to the morphology of the palm, since more erect fronds mean that less light is intercepted than if they are more horizontal (Breure, 2003). In PALMSIM, k is determined by a relationship in regard to LAI adapted from van Kraalingen (1985; Appendix).

A monthly value of 4.5 g CH_2O MJ^{-1} is used for LUE based on an optimization procedure against field data sets carried out by Combres et al. (2013). This value of LUE is used to calculate gross primary production and is therefore substantially higher than radiation use efficiency of 1.4 g CH_2O MJ^{-1} in oil palm reported by Noor and Harun (2004), which includes costs of respiration (estimated at between 60–80% of gross assimilation) and assimilates for roots.

2.2.2. Maintenance respiration and vegetative biomass production

Dufrene et al. (1990) present detailed values for the biochemical composition of the different organs. Based on this information – the nitrogen content, the mineral content, the coefficient for the conversion of nitrogen into protein, a coefficient for the costs to maintain ionic gradients and a coefficient for the renewal of free protein and membrane – they calculated maintenance respiration coefficients for roots (0.0022 g CH_2O g^{-1} day^{-1}), for the trunk (0.0005 g CH_2O g^{-1} day^{-1}), for the leaflet (0.0083 g CH_2O g^{-1} day^{-1}) and for the rachis/petiole (0.0020 g CH_2O g^{-1} day^{-1}), which are implemented in PALMSIM. Following Ng and Thamboo (1967) and Ng et al. (1968), fronds are divided into leaflets (75% of fronds) and rachis/petioles (25% of fronds). The respiration coefficient for the generative part is 0.0022 g CH_2O g^{-1} day^{-1} (van Kraalingen, 1985). The maintenance respiration coefficients are defined for a temperature of 25 °C.

The parameter for the maximum amount of assimilates allocated to vegetative production is taken from Breure (2003). 70% of these assimilates are partitioned to the fronds, and the remainder to roots (18%) and trunk (12%) growth (Henson, 2009). Growth respiration coefficients follow the calculations of tissue composition presented in Dufrene et al. (1990).

Root biomass increase is impeded over time through root mortality, which is estimated from the relationship between root mortality and root biomass in OPRODSIMv1 (Henson, 2009). Trunk growth is not considered to be limited. Standing frond biomass is controlled by pruning, which is calculated using the approach of OPRODSIMv1 (Henson, 2009).

A limit of standing frond biomass is defined by the age of the palm stand and is called fronds goal. Fronds pruned is the difference between the frond standing biomass at a certain moment in time and the corresponding value of fronds goal.

2.2.3. New fronds and flowering

The values proposed by von Uexküll et al. (2003) are used to determine the number of fronds expected for every development stage of the crop (i.e. the time after planting or the age of the

Table 1a
List of parameters used in PALMSIM related to light interception and photosynthesis.

Parameter function	Parameter term	Value	Unit	Source
Conversion rate from incoming global radiation to photosynthetic active radiation	P_{AR}	0.5	–	Monteith (1972)
Specific leaf area	S_{LA}	0.31	ha Mg^{-1}	Breure (2003)
Light extinction factor (k)	k_1	0.1	ha ha^{-1}	Adapted from van Kraalingen (1985)
	k_2	0.45	–	Adapted from van Kraalingen (1985)
	k_3	2	–	Adapted from van Kraalingen (1985)
Light use efficiency	L_{UE}	4.5	g CH_2O MJ^{-1}	Combres et al. (2013)

Table 1b
List of parameters used in PALMSIM related to maintenance respiration and vegetative biomass production.

Parameter function	Parameter term	Value	Unit	Source
Maintenance respiration coefficients				
(a) Roots	a_{roots}	0.066	Mg CH_2O Mg DM^{-1} mo^{-1}	Dufrene et al. (1990)
(b) Trunk	a_{Trunk}	0.015	Mg CH_2O Mg DM^{-1} mo^{-1}	Dufrene et al. (1990)
(c) Rachis	a_{Rachis}	0.060	Mg CH_2O Mg DM^{-1} mo^{-1}	Dufrene et al. (1990)
(d) Leaflet	$a_{Leaflet}$	0.249	Mg CH_2O Mg DM^{-1} mo^{-1}	Dufrene et al. (1990)
(e) Generative part	$a_{Generative}$	0.066	Mg CH_2O Mg DM^{-1} mo^{-1}	van Kraalingen et al. (1989)
Rachis weight in dependence on frond weight		0.75	Mg Mg^{-1}	Ng and Thamboo (1967), Ng et al. (1968)
Leaflet weight in dependence on frond weight		0.25	Mg Mg^{-1}	Ng and Thamboo (1967), Ng et al. (1968)
Maximum assimilates for vegetative biomass production	b_1	0.51	–	Breure (2003)
	b_2	0.0024	–	Henson (2009)
	b_3	0.23	–	Henson (2009)
Assimilates partitioning factor				
(a) Fronds	c_{Fronds}	0.70	–	Henson (2009)
(b) Roots	c_{Roots}	0.18	–	Henson (2009)
(c) Trunk	c_{Trunk}	0.12	–	Henson (2009)
Growth respiration coefficients				
(a) Roots	d_{Roots}	0.69	Mg CH_2O Mg DM^{-1} mo^{-1}	Dufrene et al. (1990)
(b) Trunk	d_{Trunk}	0.69	Mg CH_2O Mg DM^{-1} mo^{-1}	Dufrene et al. (1990)
(c) Fronds	d_{Fronds}	0.72	Mg CH_2O Mg DM^{-1} mo^{-1}	Dufrene et al. (1990)
(d) Male flower	d_{Male}	0.57	Mg CH_2O Mg DM^{-1} mo^{-1}	Dufrene et al. (1990)
(e) Female flower	d_{Female}	0.5	Mg CH_2O Mg DM^{-1} mo^{-1}	Dufrene et al. (1990)
Root death	e_1	0.13	–	Henson (2009)
	e_2	0.06	Mg ha^{-1} mo^{-1}	Henson (2009)
Fronds pruning	f_1	0.001	Mg DM mo^{-1} $palm^{-1}$	Henson (2009)
	f_2	0.0083	Mg DM $palm^{-1}$	Henson (2009)
	f_3	0.0006	Mg DM mo^{-1} $palm^{-1}$	Henson (2009)
	f_4	0.0636	Mg DM $palm^{-1}$	Henson (2009)
	f_5	0.16	Mg DM $palm^{-1}$	Henson (2009)

Table 1c
List of parameters used in PALMSIM related to flowering.

Parameter function	Parameter term	Value	Unit	Source
Development of new fronds	g_1	−0.039	# mo^{-1}	von Uexküll et al. (2003)
	g_2	5.3	#	von Uexküll et al. (2003)
	g_3	−0.006	# mo^{-1}	von Uexküll et al. (2003)
	g_4	3.05	#	von Uexküll et al. (2003)
	g_5	1.83	#	von Uexküll et al. (2003)
Maximum of fronds opened per palm in one time step		2.55	#	von Uexküll et al. (2003)
Fraction of flowers, which become female	h_1	−0.0045	Palm Mg DM^{-1}	Corley and Gray (1976) and Corley and Tinker (2003)
	h_2	0.9484	–	Corley and Gray (1976), Corley and Tinker (2003)
Assimilates for male flower biomass production	i_1	0.00002	ha Mg CH_2O mo^{-1} Mg DM^{-1}	Henson (2009)
	i_2	0.0006	Mg CH_2O mo^{-1} Mg DM^{-1}	Henson (2009)

plantation). A new flower is initialized at the inception of each new frond. A time period of 39 months from flower initiation to bunch harvest is assumed. Under field conditions this period might vary according to environmental conditions. For the first 15 months, flowers are asexual and thereafter become differentiated as either male or female (Corley and Tinker, 2003).

The fraction of indeterminate flowers that differentiate to female flowers decreases from 90% in the fourth year after planting to about 60% from year 15 onwards. This assumption is based on observations of Corley and Gray (1976) for coastal sites across Malaysia, who found a relationship between biomass and flower differentiation. To convert this into a time or age-driven relationship we assume an overall relationship between years after planting and biomass (based on values simulated by OPRODSIMv1) thereby obtaining a relationship between years after planting and flower differentiation. Once sex differentiation has occurred the flowers develop over 18 months until maturity and pollination. Once female flowers are pollinated, male flowers die off, and bunches develop for the next 6 months until harvest (Breure, 2003).

Quantitative knowledge on flower abortion in oil palm is lacking with little consensus about the factors that determine flower abortion, neither with regard to intensity nor timing. To capture the effects of flower abortion, an average of observations made by Corley and Gray (1976), Liau and Ahmad Alwi (1995), and Sparnaaij (1959) was taken with the resulting assumption that losses of 1% per month for indeterminate, male and female inflorescences occurred. Abortion of the inflorescence after anthesis, commonly known as bunch failure, is assumed in PALMSIM to account for 10% of total bunch loss per month (Corley and Tinker, 2003). Assimilates used for male inflorescence production are based on analyses performed with OPRODSIMv1; assimilates used for male inflorescence were plotted against total vegetative biomass for different planting densities (52, 100, 148, 196, 292 and 340 palms ha^{-1}). The resulting relationship between assimilates for total vegetative biomass and for male inflorescence is used in PALMSIM.

In PALMSIM, the assimilates that remain for biomass production of female flowers are calculated as the available gross assimilates after subtracting those used for maintenance respiration, vegetative biomass production and male biomass production, taking a growth respiration factor into account. It has been found that there is a strong relationship between gross assimilation and bunch production. This suggests that yield in oil palm is source limited (Squire and Corley, 1987; Breure, 2003), except in the case of young palms where the size of bunches may limit yield (Henson, 1990). In PALMSIM, bunch production is determined by the amount of available female flowers for the first four years of plant growth, afterwards bunch production is determined only by the available assimilates.

2.3. Model evaluation

2.3.1. Comparison of simulated versus observed data

Evaluation of model performance against observed results is a challenge as comprehensive climate and yield data sets for oil palm are scarce, as for other tree crops (van Oijen et al., 2010a; Zuidema et al., 2005). For example, Zuidema et al. (2005) limit the validation of a cocoa model to comparison between model output with regularly-reported plantation output as yield or standing biomass. Site-specific data of climate and soil were often not available. Here we use oil palm yield and frond weight data from 13 sites covering 15 trials in Malaysia and Indonesia, where optimal fertilization practices were used (Table 2). We assumed that optimum fertilized plots in environments where water is in sufficient supply are close to potential yield (van Ittersum et al., 2013). However, fertilizer rates used in the plantations included in the data set can differ from site to site, or even trial to trial. For the optimum fertilizer regimes, nitrogen rates ranged from 0.92 to 1.75 kg palm^{-1} year^{-1}, phosphorus from 0.3 to 0.8 kg palm^{-1} year^{-1} and potassium from 1 to 2.4 kg palm^{-1} year^{-1}. As controls, data from plots where no fertilizer was applied were available. Of the 13 sites, it was possible to calculate total frond production on a per hectare basis at 7 sites (9 trials, 46 observations). This was based on measurements of the average frond weight, the number of fronds per palm and the planting density. Frond dry weight was either directly available or was calculated according to Corley and Tinker (2003). The annual number of fronds produced per palm was not available for most of the sites, so an average of 22 was used (von Uexküll et al., 2003). For all sites (15 trials, 89 observations) yield as bunch production data was available. They were expressed in kg of fresh matter and converted into dry matter by assuming a commonly used dry matter content of 53% in the bunches (Breure, 2003). PALMSIM was run for every trial by taking the planting density of the palm stand into account (Table 2). Average monthly cloudiness data for the period between 2001 and 2010 for these sites were downloaded from the NASA Earth Observation website (NASA, 2012). That means an average year was used for the simulation of the whole life span of the plantation. This approach has been proposed for data scarce environments if potential growth is to be assessed for a given site (c.f. Henson, 2009). Observed frond weight and bunch production were compared with the predicted results taking the age of the palm stand into account.

For statistical analysis, the maximum observed yield and the corresponding predicted value were compared for each of the 13 sites. To assess the goodness of fit of these simulated – measured yield comparisons the root mean square error (RMSE) between predicted and observed data was calculated as follows:

$$\mathrm{RMSE} = \left[\left(\sum (\mathrm{O}-\mathrm{P})^2/n\right)\right]^{0.5}$$

where O and P are the paired observed and predicted data and n is the total number of observations.

2.3.2. Sensitivity analysis

A sensitivity analysis was carried out for the site in Sabah (Malaysia) from the available data set. 19 physiological, two management and one climate input parameters were changed by adding or subtracting 10% to the default values and the effect on annual dry bunch yield was calculated. Such an analysis will identify parameters that have a strong influence on oil palm production and therefore need to be estimated accurately (Zuidema et al., 2005).

2.4. Potential yield map for Indonesia and Malaysia

To illustrate the applicability of the PALMSIM model, it was run for all points (along a 0.1° grid) from 7° North to 6° South (latitude) and from 96° to 129° East (longitude), covering the oil palm growing regions of Malaysia and Indonesia (i.e. Borneo, Sumatra and the Malaysian Peninsular). A digital elevation model and maps of monthly average cloudiness from 2005 to 2010 were obtained from the NASA Earth Observation website (NASA, 2012). Slope and azimuth (orientation of the field with respect to the horizon) were calculated from the digital elevation model. Growth and dry bunch yield for every month for a 30 year period for each point in the grid were calculated using PALMSIM. The planting density of 143 palms ha^{-1} was used in the simulation run following the recommended practice in the oil palm industry. Maximum simulated annual dry bunch yield were transformed into FFB yield by assuming a dry weight of 53% (Breure, 2003). These FFB yields were mapped with ArcGIS 10.1.

Table 2
Overview of the available data set to evaluate PALMSIM.

Site number	Region	Planting density (ha)	Frond data available	Trial name[a]
1	Sabah	132	+	Sabah
2	Malaysia Peninsular	136	–	Jenderata
3	Lampung	143	–	Lonsum
4	North Sumatra	143	–	North Sumatra
5	Sumatra Riau	143	–	Riau Sumatra
6	South Kalimantan	136	–	South Kalimantan
7	North Sumatra	128	+	231
8	North Sumatra	128	–	232
9	North Sumatra	128	+	275
10	North Sumatra	128	+	277
11	South Eastern Sumatra	143	+	1411
12	South Eastern Sumatra	143	+	1403, 1412
13	South Eastern Sumatra	143	+	1413, 1414

[a] Trial names refer to soil type, location or planting material.

3. Results

3.1. Model evaluation

3.1.1. Single model run

For a better understanding of the simulation output generated by PALMSIM we present model output for Site 1 in Sabah (Malaysia). Simulated monthly PAR for that site ranged from 239 to 260 MJ m^{-2}, with an annual total of 2992 MJ m^{-2} (Table 3). Yearly gross assimilation was 130 Mg ha^{-1} 10 years after planting (Fig. 2a).

Maintenance respiration accounted for a loss of up to 50% in the final years and for about 40% of the total gross assimilates over the entire lifespan of the palm (Fig. 2a). While frond biomass dominated in the juvenile phase of the palm, the trunk accounted for the greatest share of the biomass in the later periods (Fig. 2b). Total vegetative biomass production remained constant after year eleven with 20 Mg ha^{-1} year^{-1} for the simulated growth period, while bunch production decreased with age (Fig. 2c).

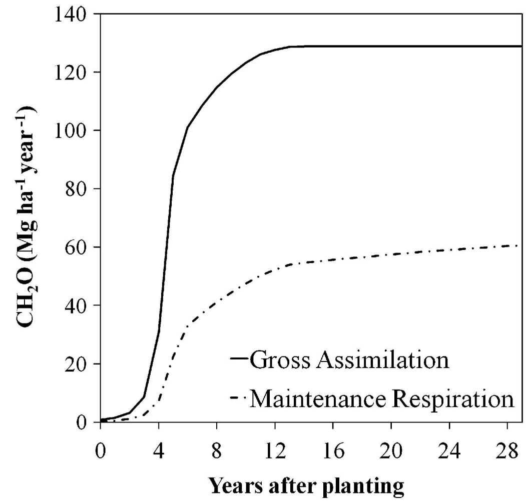

Fig. 2a. Example of the main output of the PALMSIM model for Site 1 (Sabah, Malaysia); annual gross assimilation and maintenance respiration.

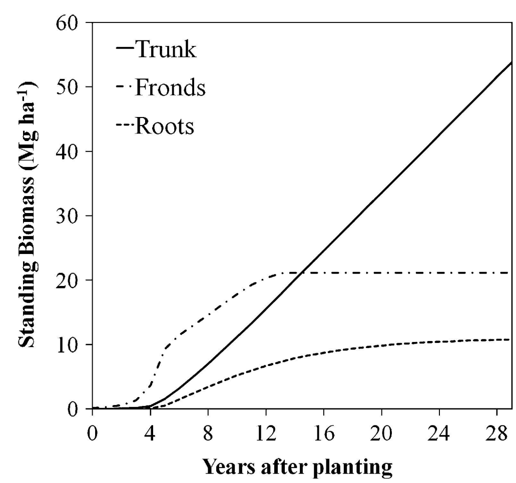

Fig. 2b. Example of the main output of the PALMSIM model for Site 1 (Sabah, Malaysia); vegetative growth.

3.1.2. Comparison with observed data

Simulated PAR for the ten-year average cloudiness data was highest in North Sumatra (3122 MJ m^{-2}) and least in Peninsular Malaysia (2866 MJ m^{-2}) (Table 3). Model predictions coincided with the largest observed frond production (Figs. 3 and 5) and yields (Figs. 4 and 6).

The maximum frond weight reached in control plots was 18.1 Mg ha^{-1}, the maximum weight in the fertilizer plot 19.2 Mg ha^{-1} and largest simulated frond weight 21.1 Mg ha^{-1}. The overall gap between predicted and observed frond weight was smaller for the fertilizer plots (4.2 Mg ha^{-1}) than for the control plots (7.6 Mg ha^{-1}). Simulated frond production over time showed a similar trend as observed fronds weight for the different ages of the palm stands (Fig. 5).

The mean gap for dry bunch weight between fertilizer and predicted plots was 3.5 Mg ha^{-1}, and for the control plots 10.0 Mg ha^{-1} (Fig. 4). The simulated mean of potential yield across all sites and ages was 19.0 Mg ha^{-1}. Overall the fertilizer plots reached 81% of this predicted yield, and the control plots 47%. Maximum observed yields for the sites ranged from 14.4 Mg ha^{-1} in Lampung (South Sumatra) to 22.4 Mg ha^{-1} in North Sumatra (Table 3). The mean for maximum observed yields and their corresponding predicted yields was 18.5 Mg ha^{-1}, and 19.3 Mg ha^{-1} respectively. The age of the palm stand varied from seven years after planting to 20 years. The RMSE for the maximum observed yields and their corresponding predicted values – 12 sites, excluding the site in Lampung – was 1.7 Mg ha^{-1} (8.75%). Overall, the simulations showed decreasing yields with age, which matched the maximum observed yields (Fig. 6)

Table 3
Maximum observed yield for each site, years after planting (YAP) of the site and the simulated dry bunch yield.

Site Nr.	Region	Years after planting	Simulated PAR (MJ m^{-2} year^{-1})	Maximum observed dry bunch weight (Mg ha^{-1} year^{-1})	Predicted bunch dry weight (Mg ha^{-1} year^{-1})
1	Sabah	18	2992	19.2	18.5
2	Malaysia Peninsular	8	2866	18.2	18.4
3	Lampung	12	3025	14.4	20.4
4	North Sumatra	11	3122	18.6	20.1
5	Sumatra Riau	20	2949	17.4	17.9
6	South Kalimantan	7	3078	19.8	20.3
7	North Sumatra	15	3110	22.4	20.2
8	North Sumatra	15	3137	17.1	20.5
9	North Sumatra	15	3080	18.3	20.0
10	North Sumatra	17	3098	21.0	20.1
11	South Eastern Sumatra	7	3048	19.7	18.1
12	South Eastern Sumatra	7	2980	16.3	17.1
13	South Eastern Sumatra	9	2917	17.4	19.7

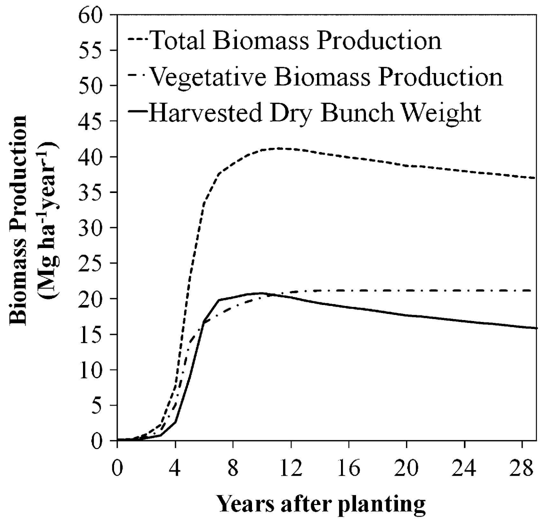

Fig. 2c. Example of the main output of the PALMSIM model for Site 1 (Sabah, Malaysia); annual total, vegetative and bunch biomass production.

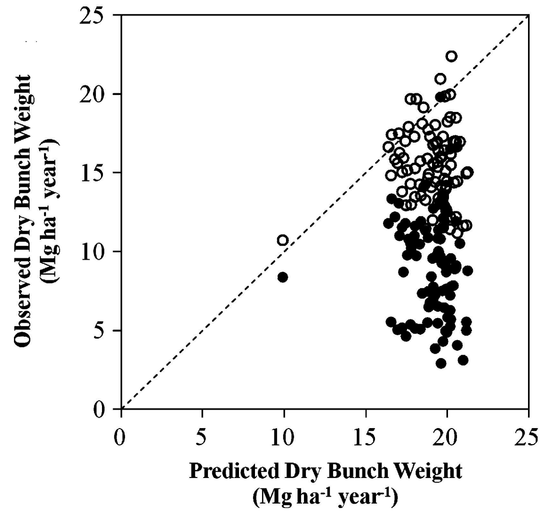

Fig. 4. Observed versus predicted dry bunch yield. Observed data from 15 trials in Indonesia and Malaysia is distinguished between optimum fertilized plots (open symbols) and control plots (closed symbols). The dotted line represents the 1:1 relationship.

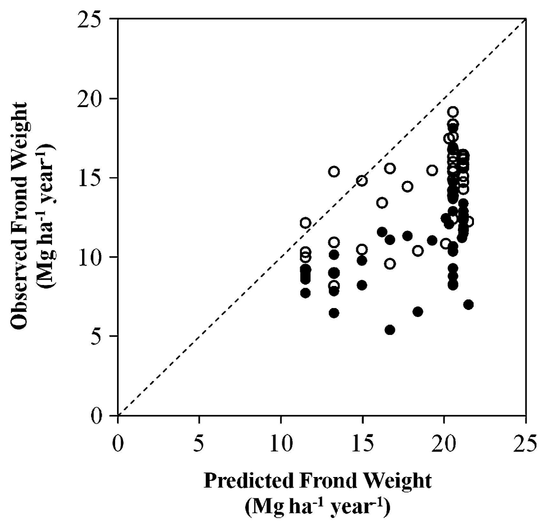

Fig. 3. Observed versus predicted frond weight. Observed data from 9 trials in Indonesia and Malaysia is distinguished between optimum fertilized plots (open symbols) and control plots (closed symbols). The dotted line represents the 1:1 relationship.

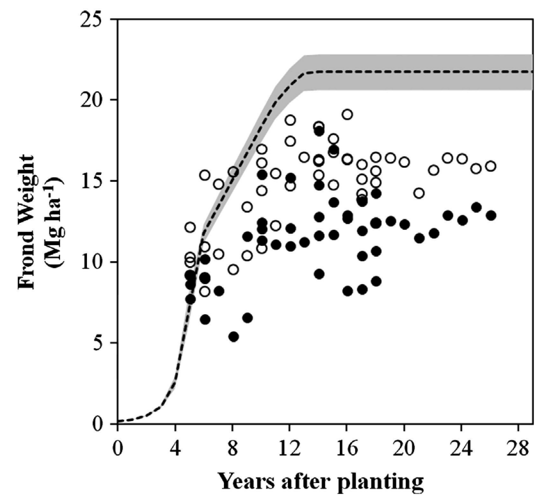

Fig. 5. Simulated potential frond weight averaged across all sites (curve) with standard deviation (gray spread) and observed frond weight across sites from fertilizer plots (open symbols) and control plots (closed symbols).

3.1.3. Sensitivity analysis

Changes in LUE had the strongest effect on dry bunch yield (12%), followed by the cloudiness index (9%), which was included in the analysis as an external driver (Fig. 7). Maintenance and growth respiration modifications lead to yield changes of slightly more than 5%. Parameters affecting the light interception (specific leaf area and the extinction factor) accounted both for about a 3% change in predicted yield. Modification of flower development only had a minor impact on predicted yield. Finally, changes of 10% in pruning and planting density, both management factors, had almost no effect on predicted yield.

3.2. Potential yield map

The largest potential yield was simulated generally for the costal sites with FFB yields of 36 Mg ha^{-1} to an absolute maximum of 48 Mg ha^{-1} (Fig. 8). Large areas of coastal plains can be found in Eastern and Southeastern Sumatra and South Kalimantan. Poor potential yields of less than 15 Mg ha^{-1}, or as little as 9 Mg ha^{-1} were predicted for the mountainous areas of Northeastern Borneo, Northern Sumatra and Central Peninsular Malaysia.

4. Discussion

4.1. Model performance

Generally, the model predicted the upper ranges of the observed yield and frond production values for a range of sites (Figs. 3–6; and a RMSE of 1.7 Mg ha^{-1} for the maximum observed yields, Table 3). Therefore the model performed well in describing potential production in the context of tree crop modeling (Zuidema et al., 2005). Other available oil palm models need detailed daily climate information (rainfall, temperature, radiation, potential evapotranspiration) (Dufrene et al., 1990; Henson, 2009). Furthermore existing crop data are required to run the models, such as annual vegetative dry matter production, leaf area index or standing vegetative biomass (Dufrene et al., 1990; van Kraalingen, 1985)

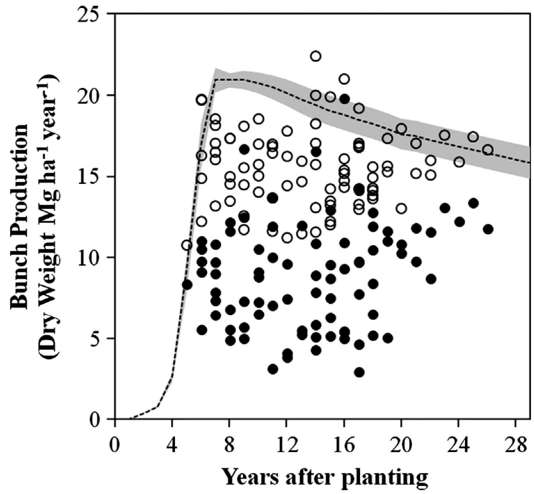

Fig. 6. Simulated potential dry bunch weight averaged across all sites (curve) with standard deviation (gray spread) and observed dry bunch weight across sites from fertilizer plots (open symbols) and control plots (closed symbols).

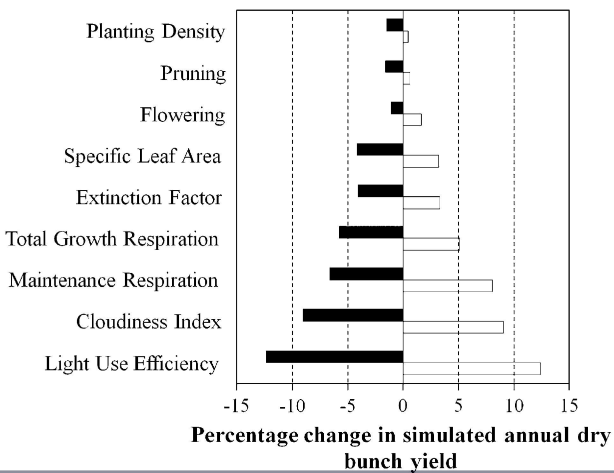

Fig. 7. Results of the sensitivity analysis for simulated potential annual dry bunch yield in Sabah. The percentage change in potential yield after increasing or decreasing the value of the parameter along the *y*-axis with 10% is shown.

or to parameterize the model (Combres et al., 2013). In depth comparisons between the performance of PALMSIM and other oil palm models cannot be made as statistical analyses of the model's performance are not available (Dufrene et al., 1990; Henson, 2009; van Kraalingen et al., 1989).

Detailed validation data sets, which allow the testing and parameterization of oil palm models in a comparable way to the validation of annual crops, are scarce (Kumar et al., 2008; van Oijen et al., 2010a). A review of the literature on tropical tree crop models showed that attempts at model testing differ from only sensitivity analysis to common statistical testing against field data for few sites. Generally, the accuracy of annual crop models is rarely reached, even though the tree models were often specifically parameterized for a given site (Combres et al., 2013; Kumar et al., 2008; van Oijen et al., 2010b; Zuidema et al., 2005;). Given the primary aim of developing PALMSIM as a model to determine potential yield across a wide range of sites, the minimal parameterization requirement is an important consideration. We follow approaches used in dynamic summary crop models for data scarce environments as for example presented by Chikowo et al. (2008). We show that PALMSIM can be tested with less detailed data sets and missing climate information, and that the model still reproduces the upper ranges of production.

Production in PALMSIM is driven by radiation alone, which can be calculated from existing cloudiness index data base of the NASA, or directly provided. This makes it easy to apply, but leads consequently to the fact that the model is strongly sensitive to the radiation regime. Changes of 10% in cloudiness lead to similar changes in the bunch yield of mature oil palm stand (Fig. 7). Similarly, the model is sensitive to the efficiency with which the intercepted radiation is used, as modification of LUE by 10% affects yield by 12%.

The simulated assimilates in the demonstration run (Fig. 2a) showed a similar pattern as observed in the field by Breure (1988) and Henson (2004) and in simulations by Dufrene et al. (1990) for Southeast Asia. It is known that maintenance respiration accounts for large losses of gross assimilates in oil palm (Corley and Tinker, 2003; Henson, 2004). Therefore the model is sensitive to changes of the maintenance coefficients. Sensitivity to the respiration coefficients is further enlarged if growth respiration is also taken into account. The demonstration run simulated roughly 40% losses due to maintenance respiration, within the range reported by Henson (2004) and Dufrene et al. (1990). While total maintenance respiration increases with standing biomass, it declines per unit biomass as observed by Henson (2004). Frond production is the dominant vegetative growth demand, but standing frond dry matter is restricted by pruning. Strict pruning management in the simulation runs causes the overlapping points for the predicted frond weight in Fig. 3. Observed values are in general below the predicted frond weights (Figs. 3 and 5), supporting

Fig. 8. Potential yield (Mg FFB ha^{-1} $year^{-1}$) map of the main oil palm regions in Indonesia and Malaysia based on simulation runs of the PALMSIM model. Simulation runs take into account incoming solar radiation, but ignore other limitations.

the assumption that the 1:1 line indeed describes potential frond growth. Possible reasons why the frond weights from the fertilizer plots do not more closely match the predicted values might be the use of average cloudiness data and the indirect calculation of frond weight. The model simulates low frond weights around the 4th year and largest weights after the 12th year, which agrees with the observed frond data (Fig. 5). However, simulated frond weight for young plantations (<4 years) are too low when compared with reported data (Henson and Dolmat, 2003). Simulated root weight is the smallest of the three vegetative simulated organs. Only limited knowledge of root growth in oil palm exists (Jourdan and Rey, 1997). The trunk has a low demand for assimilates, but it is free of growth reductions; while the total amount of frond dry matter is reduced by pruning and roots are affected by mortality. Consequently, the trunk is dominant in terms of biomass weight in mature oil palm stands (Breure, 1988). However, when compared with published data it seems that PALMSIM underestimates trunk growth. Henson (2004) reported for a sixteen year old plantation a trunk weight of 32.5 Mg ha^{-1}. In the simulation run it was only 23 Mg ha^{-1}, although total simulated standing biomass is very close with predicted 52 to measured 55 Mg ha^{-1}. Therefore frond weight is higher in the model results than the one reported (Henson, 2004). The ratio between total vegetative biomass and bunch production (bunch index) of roughly one to one in the model reflects the suggestion of Breure (2003). Similar relationships were reported by van Kraalingen et al. (1989) and Henson (2004).

After a plateau period starting from seven years onwards, bunch production starts to decline after the 10th year due to increasing losses of gross assimilates to respiration (Figs. 2c and 6). This pattern is well documented in oil palm and is supported by the comparison with observed yields (Fig. 6; Corley and Tinker, 2003). The maximum observed yield for every site closely matches the corresponding predicted yields with a RMSE of 1.7 Mg ha^{-1} $year^{-1}$ against an observed yield of 18.8 Mg ha^{-1}, with the exception of the trial in Lampung in southern Sumatra (Table 3). The larger yield gap in Lampung in comparison with the other sites suggests that factors other than radiation limit yield in this trial. Oil palm production in Lampung seems to be strongly limited in several years by a lack of sufficient water. Generally, the direct impacts of water shortages on yield in oil palm are not easy to define due to the long time-lag between initiation of the flowers and fruit bunch production (Carr, 2011).

Observed yields from the optimum fertilizer plots across all sites reach 81.4% of the average simulated potential yield; the unfertilized control plots only 47.5%. Possible explanations why the some of the observed yields of the fertilized plots are not closer to the potential yields could be that the growth and yield of the palm stand, even in these favorable production regions, is affected in some years and sites by water shortage (a limiting factor) and heat stress (a defining factor), which are both not taken into account by the model. Carry over effects of production stress in previous years could be present in the observed yields, but no information was available to study this. Given these shortcomings, the current version of the PALMSIM model cannot be used as a site-specific decision making support tool to address questions such as when the harvest peak for the bunches in a specific year can be expected. However, given that radiation is the major yield determining factor on a regional scale across Borneo, Sumatra and the coastal areas of the Malaysian Peninsular, PALMSIM can be a valuable tool to explore potential yield on a wider scale (Corley and Tinker, 2003).

The evaluation against field data shows that the model predicts reasonable potential yields. The sensitivity analysis demonstrates that PALMSIM is robust, although specific attention has to be paid to the LUE, which needs careful parameterization. Changes in terms of yield by modifying the parameters by 10% are comparable to other tree crop model evaluations (Dufrene et al., 1990; Zuidema et al., 2005).

4.2. Mapping potential yield of oil palm for Indonesia and Malaysia

The capability of PALMSIM to estimate potential yield for large areas is shown in Fig. 8. Sites situated in mountainous areas receive on average less PAR due to increased cloud cover in the mountains in comparison with the lowland. This difference is particularly pronounced during the dry months. This is important for the mountainous areas of Borneo in the northeast, the highlands in the center of the Malaysian Peninsular and the hilly sites of north western Sumatra. Western Sumatra is dominated by a chain of mountains, which results in a relatively small potential yield. The favorable sites in terms of radiation are mainly coastal areas. The simulation results reproduce the known trend that actual yields are larger in coastal plains, where FFB yields above 40 Mg ha^{-1} have been reached (Corley and Tinker, 2003; Donough et al., 2009).

However, the map suggests that there are large areas in Southeast Asia with potential yields above 30 Mg FFB ha^{-1} $year^{-1}$. The gap between potential yields and average reported yields from the plantations directly leads to the question of the most important growth limiting and reducing factors. In regions with high rainfall (more than 2500 mm) and good soils, yields of more than 30 Mg ha^{-1} are possible as discussed by Corley and Tinker (2003). The fertilizer trial results show that it is possible to reach simulated potential yields, at least at plot level. Exploring the gaps caused by nutrient limitations and biotic stresses could improve yields significantly as shown by Donough et al. (2009). Overall our results suggest a need to investigate this gap further and to identify attainable yield levels.

The presented regional map based on PALMSIM simulations (Fig. 8) can contribute to the second proposed strategy for sustainable oil palm production; the cultivation of marginal sites in Indonesia and Malaysia. Identifying appropriate degraded sites with high potential yields is a challenge (Corley and Tinker, 2003). The map can be used to select preferable regions for surveys and land use planning for oil palm. However, the simulated potential yields assume optimum conditions, which are rarely achievable. Oil palm production is affected in certain years by water shortages even in Indonesia and Malaysia (Carr, 2011). Water availability from year to year and soil constraints affecting water storage and supply in relation to the impacts of water stress on growth and production of oil palm would have to be included to simulate water-limited yields. Despite these considerations the yield gap between potential yield and water-limited yield in Indonesia and Malaysia is likely to be small in comparison to other regions such as West Africa or Thailand, where oil palm expansion currently takes place (Carr, 2011; Corley and Tinker, 2003).

To identify suitable sites for the expansion of oil palm production it is necessary to combine this potential yield map with existing maps within the marginal areas for factors such as soil type, rainfall, infrastructure and land rights as recently published by the World Resource Institute for Kalimantan (Gingold et al., 2012).

4.3. Limits and future necessary improvements of PALMSIM

Models can play an important role in identifying the growth limiting and reducing factors and quantifying their effects across large regions. Such a yield gap analysis could contribute to the identification of appropriate intensification strategies for existing plantations. Available oil palm production models are not yet capable of such a wide range analysis. Despite their potential usefulness in decision support and yield gap assessments as discussed above, the development of physiological growth models for tree crops is still in its infancy, not only in terms of validation but also in the description and parameterization of the physiological processes (van Oijen et al., 2010a,b). The lack of detailed data sets is a major constraint in this context. Therefore the challenge is to develop PALMSIM further by taking water, nutrient and other limitations into account and keeping the data input low that it can be tested with available data sets and applied across a wide range of scales. Improvements in monitoring daily weather at oil palm plantation sites would be of great benefit to provide the high quality climate data needed by the model and could replace the current approach in PALMSIM that calculates radiation data indirectly using satellite derived cloudiness images.

5. Conclusion

We present a relatively simple model, PALMSIM, to simulate the potential growth and yield of oil palm. The model performed well against field data from several sites across Malaysia and Indonesia and a sensitivity analysis showed that the model is robust. PALMSIM can simulate potential yield of oil palm for a wide range of sites. When combined with information on soil and other maps of marginal sites, such simulation results may be used to support the selection of potential new sites for oil palm plantations. Priority for future work with the PALMSIM model is incorporating effects of water stress on biomass production and yield.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agsy.2014.07.006.

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